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**NASA F-16XL SUPERSONIC LAMINAR FLOW CONTROL  
PROGRAM OVERVIEW**

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## OBJECTIVES OF THE F-16XL SUPERSONIC LAMINAR FLOW CONTROL EXPERIMENT

Successful application of laminar flow control to a High Speed Civil Transport (HSCT) offers significant benefits in reductions of take-off gross weight, mission fuel burn, cruise drag, structural temperatures, engine size, emissions and sonic boom ( refs. 1-3). The ultimate economic success of the proposed HSCT may depend on the successful adaption of laminar flow control, which offers the single most significant potential improvement in L/D of all the aerodynamic technologies under consideration. The F-16XL Supersonic Laminar Flow Control (SLFC) Experiment was conceived based on the encouraging results of in-house and NASA supported industry studies (refs. 1-3) to determine if laminar flow control is feasible for the HSCT. The primary objective, as illustrated in figure 1, is to achieve extensive laminar flow (50-60 percent chord ) on a highly swept supersonic wing. Data obtained from the flight test will be used to validate existing Euler and Navier Stokes aerodynamic codes and transition prediction boundary layer stability codes. These validated codes and developed design methodology will be delivered to industry for their use in designing supersonic laminar flow control wings. Results from this experiment will establish preliminary suction system design criteria enabling industry to better size the suction system and develop improved estimates of system weight, fuel volume loss due to wing ducting, turbocompressor power requirements, etc. so that benefits and penalties can be more accurately assessed.

### **F-16XL SHIP 2 SUPERSONIC LAMINAR FLOW CONTROL EXPERIMENT**

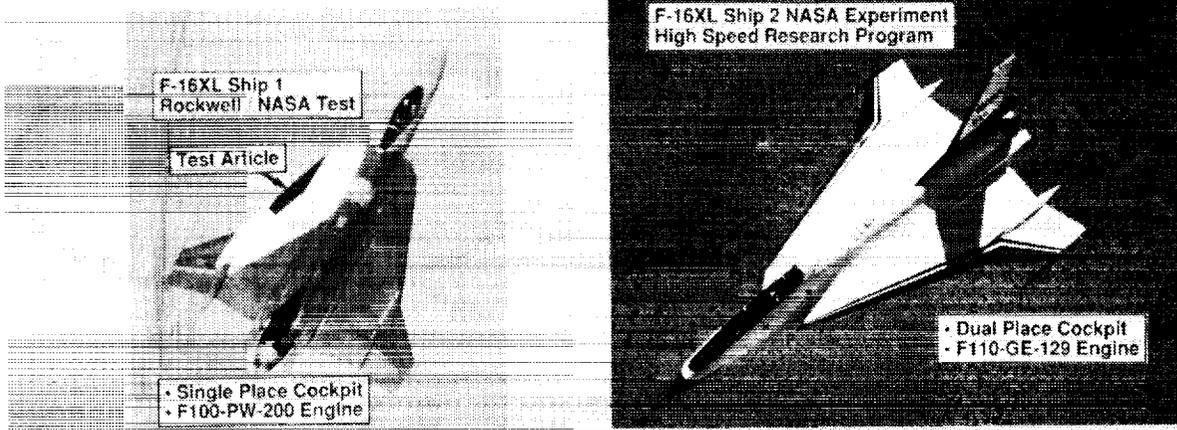
#### **OBJECTIVES**

- **Achieve 50-60% chord laminar flow on a highly swept wing at supersonic speeds**
- **Deliver validated CFD codes and design methodology to industry for designing supersonic laminar flow wings**
- **Establish initial LFC suction system design criteria to allow industry to more accurately integrate concept into HSCT and determine benefits**

## F-16XL SUPERSONIC LAMINAR FLOW CONTROL FLIGHT TESTING

There are two F-16XL aircraft involved in supersonic laminar flow flight testing. The F-16XL was chosen for the experiment because it has a highly swept cranked wing planform that closely resembles the HSCT configurations proposed by industry. The inboard section of the wing is swept 70 degrees, while the outboard section is swept 50 degrees. The F-16XL Ship 1 has a single place cockpit (see figure 2) and is currently being utilized in a cooperative laminar flow control flight test program involving North American Rockwell International and NASA. The objectives of the Rockwell/NASA program are to develop and validate CFD methodology and demonstrate that laminar flow is achievable to a limited chord extent on a highly swept wing at supersonic speeds. The laminar flow control test article on Ship 1 is considerably smaller in span and chord extent as compared to the planned NASA experiment on Ship 2, thus extensive laminar flow will not be demonstrated on Ship 1. Also, the airfoil section and pressure distribution on the Ship 1 test article is different than that planned for the NASA experiment on Ship 2. Flight testing began on Ship 1 in May, 1990. Flight data obtained from Ship 1 has proven to be very informative and useful in reducing the risk for the NASA Ship 2 experiment. Ship 1 flight data is being utilized to calibrate Euler and Navier Stokes codes and boundary layer stability codes. F-16XL Ship 2, which has a two place cockpit, as shown in figure 2, arrived at DFRF in February, 1991 and is being instrumented for flight testing.

### SUPERSONIC LAMINAR FLOW CONTROL FLIGHT TESTING

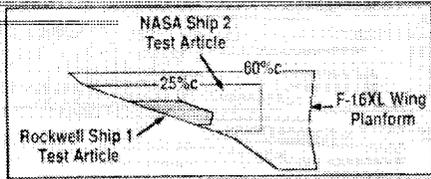


**Objectives:**

- Develop and Validate CFD Methodology
- Demonstrate Laminar Flow Achievable on a Highly Swept Wing at Supersonic Speeds

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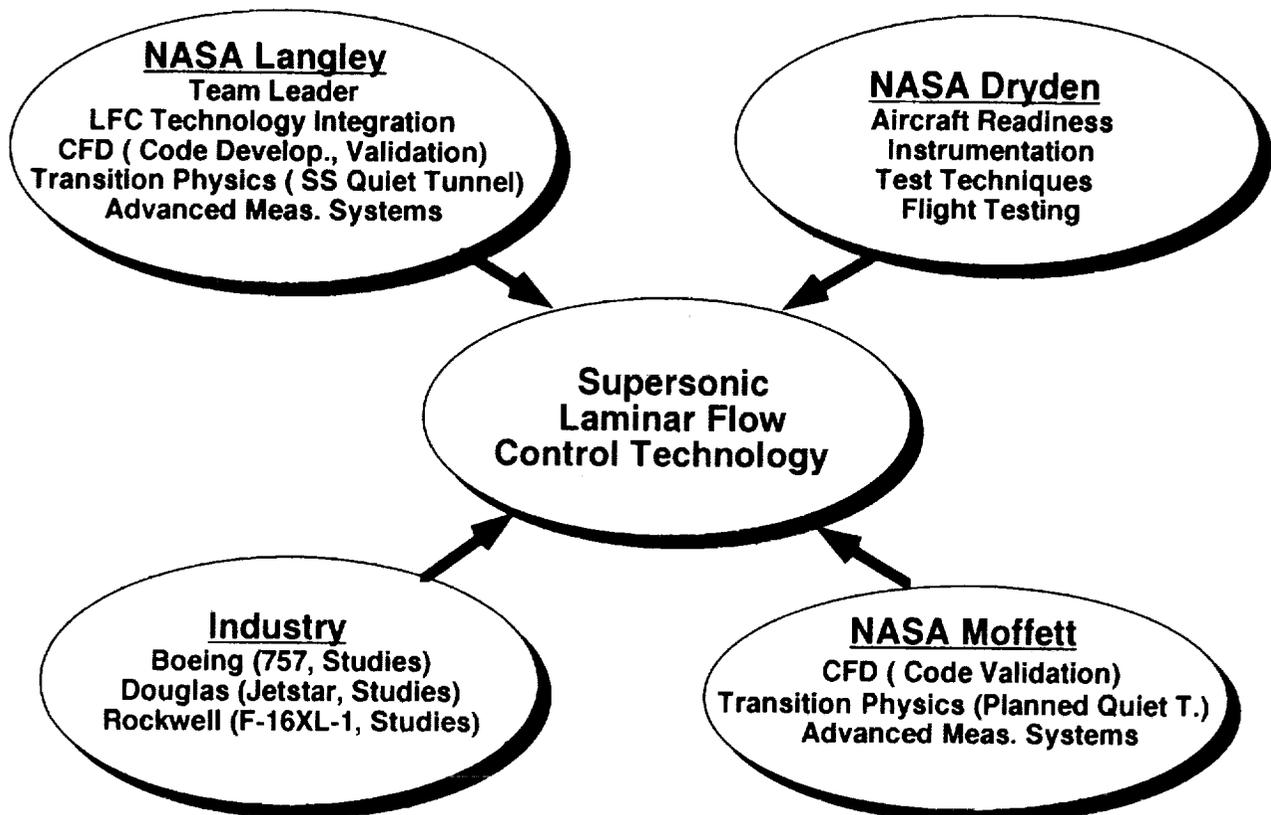
- Achieve 50-60% Chord Laminar Flow on a Highly Swept Wing at Supersonic Speeds
- Deliver Validated CFD Codes and Design Methodology to Industry for Designing Supersonic Laminar Flow Wings
- Establish Initial LFC Suction System Design Criteria



## NASA / INDUSTRY TEAM APPROACH ON THE F-16XL SLFC EXPERIMENT

To carry out the F-16XL experiment, NASA has structured a combined NASA / Industry team approach to take advantage of the broad LFC experience base within Industry and NASA (see figure 3). NASA Langley has overall responsibility for management of the program, based on its proven LFC technology expertise and integration capabilities established over numerous successful laminar flow flight programs. Langley is also responsible for Navier Stokes and Euler code validation, transition prediction methodology through both boundary layer stability code development and validation and transition experiments with swept model tests in the Supersonic Low-Disturbance Pilot Tunnel, and advanced measurement systems. NASA Dryden is responsible for aircraft readiness, instrumentation, test techniques and flight testing. NASA Moffett is responsible for Navier Stokes and boundary layer stability code validation, transition experiments in a planned low disturbance supersonic wind tunnel, and advanced measurement systems. The industry team which has laminar flow control flight experience consists of Boeing, Douglas and Rockwell. These three companies are also participating in LFC technology studies for NASA. Industry involvement is essential to ensure practical, relevant LFC technology is developed and validated and to ensure rapid transfer of the technology to application. A contractor to be chosen in a competitive procurement will be responsible for the design, fabrication and installation of flight test hardware and associated systems on the F-16XL Ship 2.

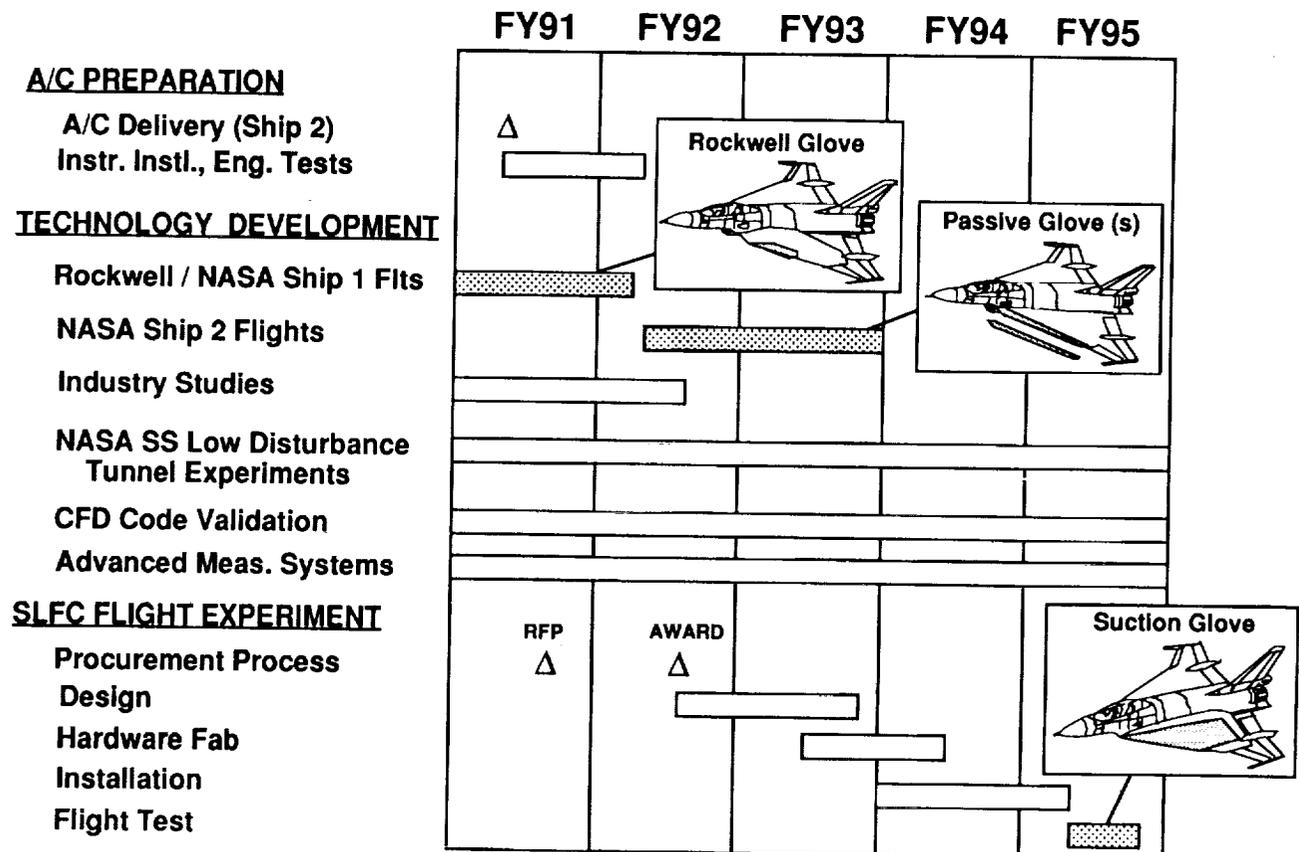
### NASA / INDUSTRY TEAM APPROACH ON F-16XL SLFC EXPERIMENT



## SCHEDULE FOR THE F-16XL SUPERSONIC LAMINAR FLOW CONTROL EXPERIMENT

The activities leading to the eventual flight experiment on the F-16XL-2 are shown in figure 4. F-16XL-2 arrived at DFRF in February, 1991 and is currently being instrumented for flight testing. Prior to the actual Ship 2 suction panel laminar flow control experiment, there is a need to reduce the risk to the experiment by developing key technologies through industry studies, obtaining flight and supersonic wind tunnel data for design criteria and code calibration, and evaluating advanced instrumentation. The initial series of Rockwell/NASA Ship 1 flight tests will be completed and followed by proposed NASA tests to determine suction level-laminar flow sensitivities and obtain other useful data. Leading-edge passive gloves will be flight tested on Ship 2 to obtain attachment-line design criteria and surface pressure and transition location data for code calibration. Swept wing suction and non-suction models will be tested in supersonic low disturbance tunnels to obtain attachment line and crossflow stability data for comparison with flight data and establishment of design guidelines. The CFD code validation effort will be a continuing refinement process as flight and wind tunnel data become available. The request for procurement (RFP) package will be released in June 1991 with award expected in April 1992. The contractor chosen will be responsible for designing, fabricating and installing the test hardware and related suction system. Flight testing to demonstrate achievement of extensive laminar flow is scheduled to conclude in late FY95.

### F-16XL SLFC EXPERIMENT SCHEDULE



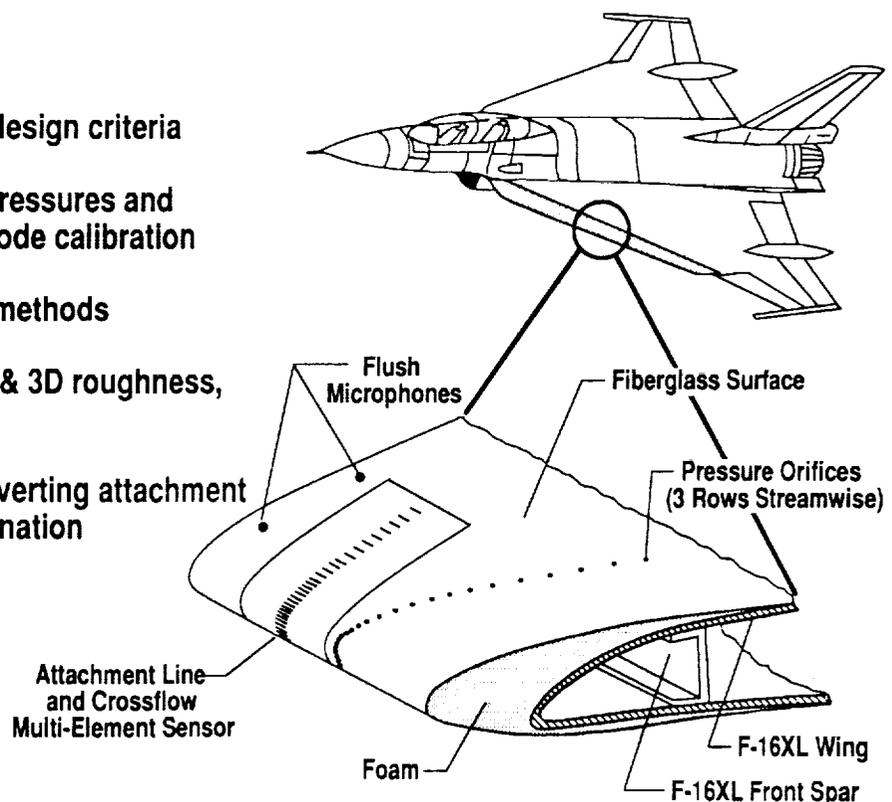
## F-16XL-2 LEADING EDGE PASSIVE GLOVE(S)

Proper design of the leading-edge region is crucial to ensure control of spanwise leading-edge turbulence contamination, and to prevent unacceptable growth of both attachment line boundary layer disturbances and crossflow disturbances. This design process will involve careful tailoring of the leading edge radius and local suction level. There is limited leading-edge transition data available at supersonic conditions, so a non-suction leading-edge passive glove will be designed and flight tested on Ship 2 to provide needed design criteria and reduce the risk for the NASA experiment (see figure 5). Momentum thickness Reynolds number ( $R_{\theta}$ ) limits for transition of the attachment line with no suction will be obtained and compared with theoretical calculations. Transition on the upper surface due to crossflow will also be determined for a range of leading-edge surface pressure accelerations. The transition and surface pressure data will be used to calibrate stability and CFD codes and improve existing transition prediction methods. The passive glove tests will also provide the opportunity to evaluate advanced measurement methods, such as multi-element sensors, improved anemometers and flow visualization techniques. Both 2D steps and 3D roughness effects on leading-edge laminar flow will be explored to provide design criteria for suction panel joints and acceptable insect accretion height. It may be possible to provide the needed flight data with one passive glove operating at both design and off-design conditions, however, if required and the schedule permits, a second glove could be evaluated.

## F-16XL LEADING-EDGE PASSIVE GLOVE(S)

### **Objectives:**

- Obtain attachment line design criteria
- Measure leading-edge pressures and transition location for code calibration
- Evaluate measurement methods
- Determine effects of 2D & 3D roughness, steps, on laminar flow
- Evaluate methods for diverting attachment line turbulence contamination



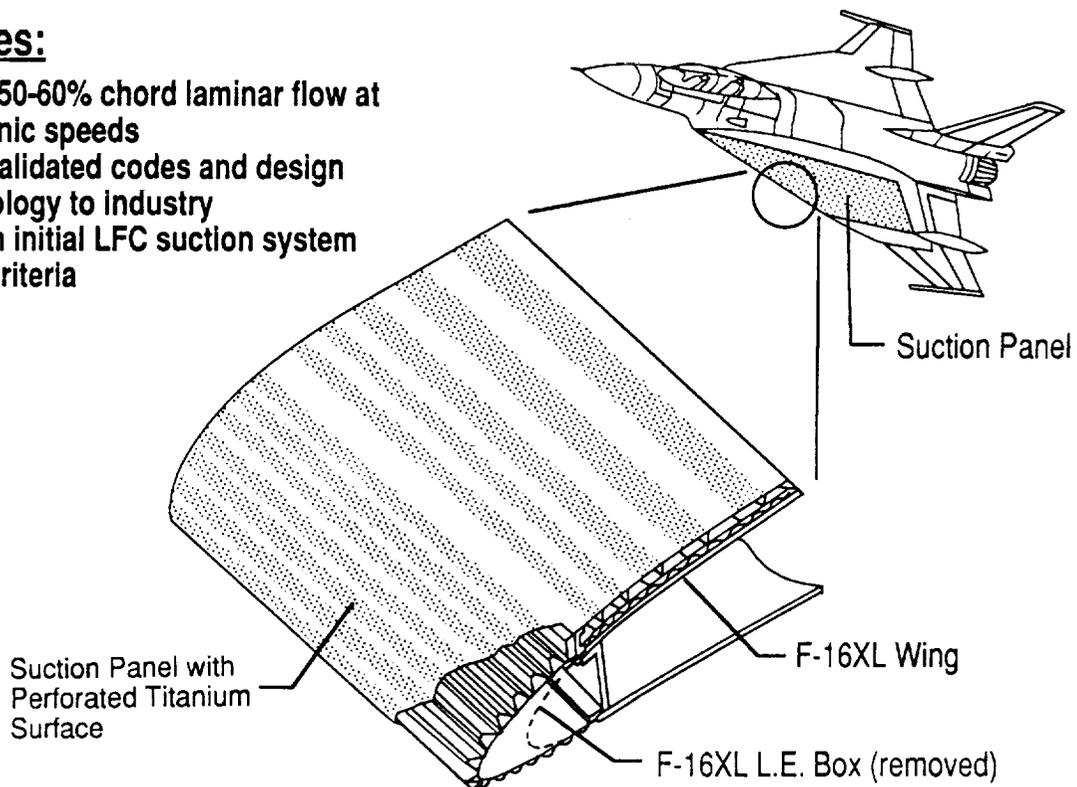
## F-16XL-2 SUPERSONIC LAMINAR FLOW CONTROL EXPERIMENT

The NASA experiment will involve flight testing an active suction panel(s) to achieve laminar flow to 50-60 percent chord, as illustrated in figure 6. The test article will be designed to achieve laminar flow over a range of Mach numbers and altitudes to provide laminar flow data for a wide variation in pressure distributions, unit Reynolds number, and attachment line conditions. Suction flow rate level and distribution will be varied in flight to determine the sensitivity of laminar flow extent to changes in suction flow, pressure distributions and Reynolds numbers. These flight data will be extremely valuable in validating the Euler and Navier Stokes codes and the boundary layer stability codes. These validated codes will enable the establishment of a design methodology for designing supersonic laminar flow control wings which will be delivered to industry for their use. Data from the experiment should also provide preliminary estimates for LFC system sizing to allow Industry to more accurately determine the benefits and penalties of LFC. It is important to recognize that the F-16XL SLFC Experiment is an aerodynamic feasibility experiment and not a technology demonstration program. Before industry will implement laminar flow control on a HSCT, a high confidence level in such areas as performance, cost, reliability, maintainability, safety, system and structural integration, etc. must be demonstrated. To achieve these goals, a parallel NASA / Industry program must be developed and initiated in the near future to address those critical technologies not being pursued in the F-16XL SLFC Experiment.

## F-16XL-2 SUPERSONIC LAMINAR FLOW CONTROL EXPERIMENT

### Objectives:

- Achieve 50-60% chord laminar flow at supersonic speeds
- Deliver validated codes and design methodology to industry
- Establish initial LFC suction system design criteria



## ACCOMPLISHMENTS

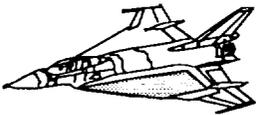
In the past year, there have been many significant accomplishments in the program, as shown in figure 7. Flight data on the F-16XL-1 has been obtained and is being used to calibrate Navier Stokes and boundary layer stability codes. Navier Stokes solutions of the complete F-16XL configuration have been obtained with several codes. A re-start of testing on the F-16XL-1 is planned in the near future to map out the transition front across the test article for a range of flight conditions. Planning for NASA follow on F-16XL-1 tests is underway also. The F-16XL-2 vehicle arrived at DFRF in February and is now being instrumented for flight testing. A NASA sponsored study performed by DAC indicated the feasibility of achieving 60 percent chord laminar flow on F-16XL-2. A leading-edge passive glove design for the F-16XL-2 is underway and is scheduled for testing in early calendar year 1992. Blockage models were successfully tested in the LaRC Supersonic Low-Disturbance Tunnel and a non-suction thin-skin instrumented model is being fabricated for testing in July, 1991. Thin-film micro-element sensors were further developed, tested in several wind tunnels and designed/fabricated for the F-16XL leading-edge. The F-16XL RFP procurement package was prepared with release scheduled for June 1991. Industry technology study tasks have been identified and are being implemented to address "technology holes".

## **ACCOMPLISHMENTS**

- Rockwell / NASA F-16XL-1 flight data obtained, tests nearing re-start
- Plans for follow-on F-16XL-1 tests being finalized
- Navier Stokes F-16XL-1 solutions obtained, codes being calibrated with flight data
- F-16XL-2 arrived February, 1991 at DFRF, instrumentation being installed
- DAC study indicated feasibility of achieving 60% c laminar flow on F-16XL-2
- Passive glove design for F-16XL-2 tests underway
- Non-suction model for LaRC SS Low-Disturbance Tunnel being fabricated, testing begins July 1991
- Micro-element sensors developed and tested in wind tunnels, designed and fabricated for F-16XL
- F-16XL-2 RFP procurement package being prepared, release scheduled for June 1991
- Industry technology study tasks being initiated to address " technology holes"

## SUMMARY

NASA has carefully tailored the program to achieve a balance of both NASA and industry participants to take advantage of the laminar flow control expertise available. There is also a proper mix of computational effort, ground facility experiments, and flight testing. Flight tests with the Rockwell laminar flow control test article on F-16XL-1 is providing useful data that will reduce the risk for the F-16XL-2 experiment. Leading-edge passive glove tests on F-16XL-2 will provide attachment line design criteria and code calibration data that will add confidence to the design process for the suction panels. The RFP for the design, fabrication and installation of suction panel(s) and associated suction system hardware is scheduled for release to industry in June 1991 and award in April 1992. Flight testing of the active suction panel(s) will be conducted in 1995.



## **SUMMARY**

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- Program has a balance of participants and technologies
  - NASA- industry roles
  - CFD, wind tunnel tests, flight tests
- Flights with F-16XL-1 have been, and continue to be, informative & will reduce risk for F-16XL-2 experiment
- Passive glove testing on F-16XL-2 will provide attachment line criteria and code calibration data
- Plan to issue RFP to industry for design, fabrication and installation of suction panel(s) and associated suction hardware in June 1991
- Flight test active suction panel(s) in 1995

## REFERENCES

1. Powell, A. G.; Agrawal, S.; and Lacey, T. R.: Feasibility and Benefits of Laminar Flow Control on Supersonic Cruise Airplanes. NASA CR 181817, July 1989.
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3. Pfenninger, W.; and Vemuru, C.S.: Design Aspects of Long Range Supersonic LFC Airplanes Especially With Highly Swept Wings. SAE Paper No. 881397, 1988